AN EIGHT-YEAR EXPERIMENT IN IMPROVING FORECASTS OF HURRICANE MOTION

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ABSTRACT

The National Hurricane Center and the National Hurricane Research Laboratory joined forces in an effort to improve techniques for forecasting hurricane motion in the spring of 1959 when the latter moved its headquarters from West Palm Beach to Miami into offices adjacent to those occupied by the principal hurricane forecast office in the United States. Results now available from verification of forecasts made during the period 1954 through 1966 show that there has been a significant improvement in the accuracy of hurricane forecasts during the period of increased cooperation between the research and operational forecasting groups. This improvement is indicated by a reduction in the mean error of hurricane forecasts of approximately 10 and 12 percent, respectively, for the two principal hurricane forecast areas near the eastern coasts of the United States.

1. INTRODUCTION

Furnishing the public with advices and warnings of severe weather has always been a primary mission of the U.S. Weather Bureau. Since hurricanes are one of the most important of the severe weather types, the Weather Bureau has consistently assigned proven forecasters to the hurricane service. Through the years empirical rules have been formulated for forecasting hurricane motion and these were handed on from forecaster to forecaster. The forecast furnished the public, however, was always the result of the subjective judgment of an experienced forecaster. In the 1950's various individuals and small groups started developing objective techniques for making the predictions. A summary of these early attempts has been prepared by Gentry [2]. Pioneers in this field were Riehl, Haggard, and Sanborn [10] who developed regression equations utilizing 500-mb. data read from a grid centered on and moving with the hurricane. At about the same time there were other experimenters at the Travelers Research Center [13] and in the Weather Bureau [3, 4, 9] who developed techniques—some based on statistical-climatological approaches and others based on dynamical models.

In the spring of 1959 the National Hurricane Research Laboratory moved into new quarters adjacent to those occupied by the forecasters of the National Hurricane Center. A cooperative program was established between the forecasters and the researchers which led to some of the improvement in accuracy of forecasts which is reported herein.

Among the primary missions of the National Hurricane Research Laboratory has been the evaluation of existing techniques and the development of new ones for forecasting hurricane motion. One of the reasons for moving the laboratory to Miami was to expedite this work and to make it more convenient to have a cooperative program with the forecasters. The senior authors of this paper have been the directors of the National Hurricane Center and the National Hurricane Research Laboratory, respectively, throughout the period of the experiment. Dr. Banner I. Miller has led the research efforts in the area of forecasting hurricane motion. Mr. Paul L. Moore was a senior hurricane forecaster in the center at Miami throughout the period of the experiment and during the later years was the supervising hurricane forecaster. Both he and Mr. Harry F. Hawkins, Assistant Director of the National Hurricane Research Laboratory, actively participated in the planning of the cooperative program and contributed ideas to the research program. Miller and Moore [9] developed one of the objective forecasting techniques which was available for testing in 1959.

The cooperative program implemented in 1959 consisted of the following approaches: 1) joint map discussions were held each day during the active portion of the hurricane season between the forecasters and the research workers at Miami; 2) the forecasters were solicited for suggestions for developing improved techniques; 3) a research group endeavored to develop improved objective techniques for forecasting hurricane motion; 4) contract work was supported by the Research Laboratory in groups outside the Weather Bureau for improving forecasting techniques (for example see [5, 6, and 14]); 5) forecasts of hurricane motion based on the better objective forecast techniques were prepared under semioperational conditions by the research laboratory for the use of the forecaster; and 6) all forecasts, both those made by forecasters and those made by the objective techniques, were verified routinely in order to identify the more promising forecast methods.

2. RESULTS OF THE FORECAST EXPERIMENT

Since the experiment began, the average errors of the official forecasts of hurricane motion prepared by the Weather Bureau for periods 24 hr. in advance have been

*Retired January 13, 1968.

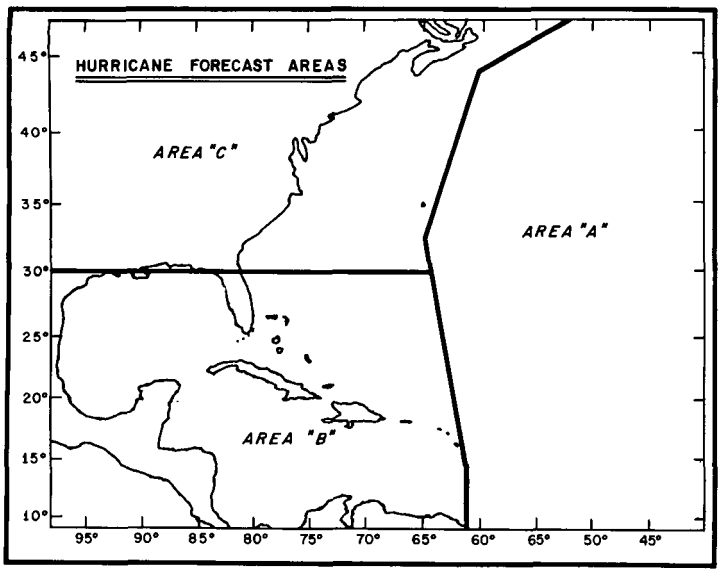

FIGURE 1.—Areas used in grouping the hurricane forecasts for verification.

reduced 10 percent and 12 percent, respectively, for the two principal forecast areas near eastern United States.[1]

In the beginning it was realized that the average error in forecasts of hurricane motion would vary considerably with the amount of data available to the forecaster and, to some extent, with latitude. To obtain more representative verifications, a program was designed to verify the forecasts for three different areas, which are illustrated in figure 1. In *Area A* there are relatively few upper air data for the use of the hurricane forecasters. *Area B* is the one in which upper air data are most plentiful. *Area C* also has many more data than area A but has fewer data than does area B. Because of variation in data availability the forecast errors should be largest in area A and smallest in area B. Forecast errors in area C may be larger than those in area B for another reason; namely, when storms have recurved into the westerlies the rate of movement frequently becomes quite large which could cause the magnitude of the error to be greater.

The effective size of area A has varied with time since the beginning of the forecast verification program. The availability of satellite data in recent years has encouraged forecasters to start issuing advisories when storms were farther east of the data network. During the later years this has resulted in forecasts frequently being issued for storms for which relatively few upper air data were available to assist the forecaster. Also, for storms which have recurved into the westerlies the tendency in recent years has been to continue issuing forecasts for additional days. Thus, it is difficult to obtain a representative variation with time of the forecast errors for area A because the portion of area A in which hurricane forecasts were made has not remained constant. Areas B and C, however, have been the same in size and relatively homogeneous insofar as amount of available data throughout the period. The upper air data network was somewhat better in area B in the earlier years of the period than it has been in recent years. To the extent that this has influenced the forecasts, there should have been a slight deterioration in forecast accuracy with time, particularly during the last 6 yr. This has been balanced, however, by more frequent aircraft reconnaissance of hurricanes and better information about location of the hurricane center at beginning of forecast periods.

TABLE 1.—*Mean errors in 24-hr. forecasts of hurricane motion*

Year	Area B		Area C	
	Mean error (n.mi.)	Number of forecasts	Mean error (n. mi.)	Number of forecasts
1954	133	60	194	35
1955	112	117	174	32
1956	146	32	152	21
1957	144	28	253	12
1958	118	77	174	27
1959	144	61	131	27
1960	105	59	205	19
1961	113	96	173	33
1962	142	30	187	33
1963	116	79	189	30
1964	95	94	142	51
1965	124	65	103	2
1966	113	101	171	25

The Weather Bureau began making forecasts of hurricane positions for 24 hr. in advance in 1954. These forecasts have been largely for internal governmental use but have been recorded consistently since that year. Table 1 gives the average error of hurricane forecasts by years in areas B and C for the periods 1954 to 1966. These data are illustrated by the broken lines in figures 2 and 3. Error here means the distance in nautical miles between forecast and observed positions of the hurricane center at the end of the 24-hr. forecast period. Note that there has been considerable variation from year to year in the average error. In general, however, the trend has been downward. This trend becomes more noticeable if the average error is computed by 3-yr. periods which overlap. The results of such computations are illustrated by the solid lines in figures 2 and 3.

The variation of the average forecast errors with time is also related to different periods in the experiment in figures 2 and 3. The average error for the 5 yr. prior to initiation of the experiment (1954–58) is considered a base for comparison with later periods. The following 8 yr. (1959–1966) are divided into two periods. The graphs show a progressive reduction of the average error for each of these periods of 4 yr. for both areas B and C. The average error for 1963–66 was less than the average error for 1954–59 by 10 percent in area B and by 12 percent in area C. When using the t test of significance between two sample means with unpaired variates these differences are significant at the 5-percent level for area B and at the 10-percent level for area C.

The mean errors in the forecast for 1967 were considerably lower than those in 1966 for both areas B and C. They are not included in figures 2 and 3 for three reasons: 1) desire to keep the comparison by 4-yr. periods, 2) the

[1] In this study the primary concern is with the change in forecast accuracy during the years. A more complete explanation is contained in a detailed treatment of the hurricane forecast verification results prepared by Tracy [11]. His data were used in this paper.

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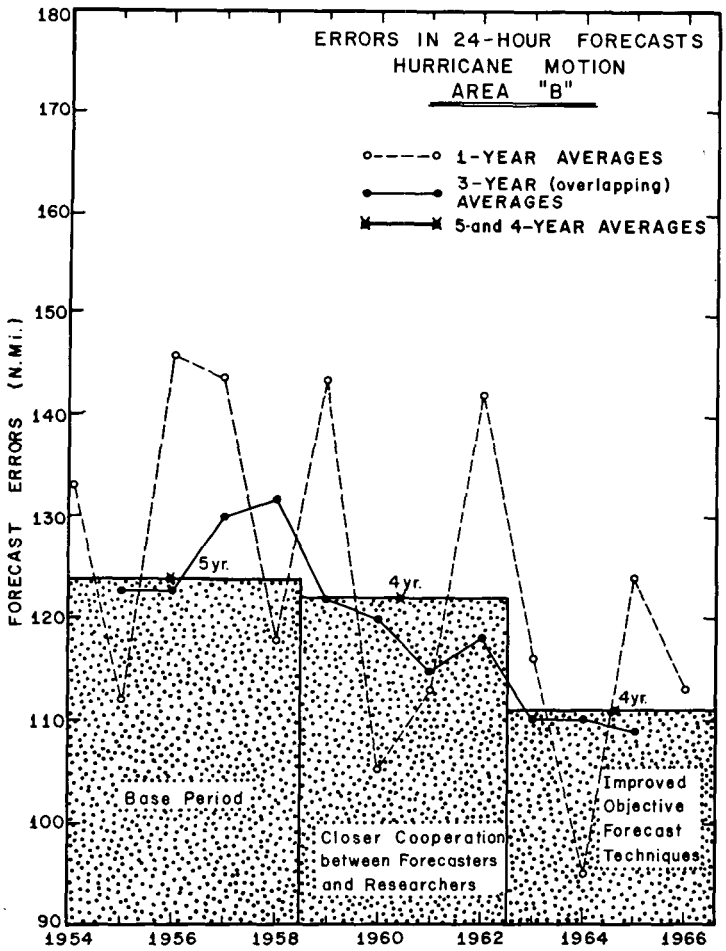

FIGURE 2.—Variation by years of the mean errors in Weather Bureau 24-hr. forecasts of hurricane motion for area B. Broken line connects yearly averages of the errors, solid line connects overlapping 3-yr. averages of the errors, and dotted bar graphs represent mean errors for longer periods.

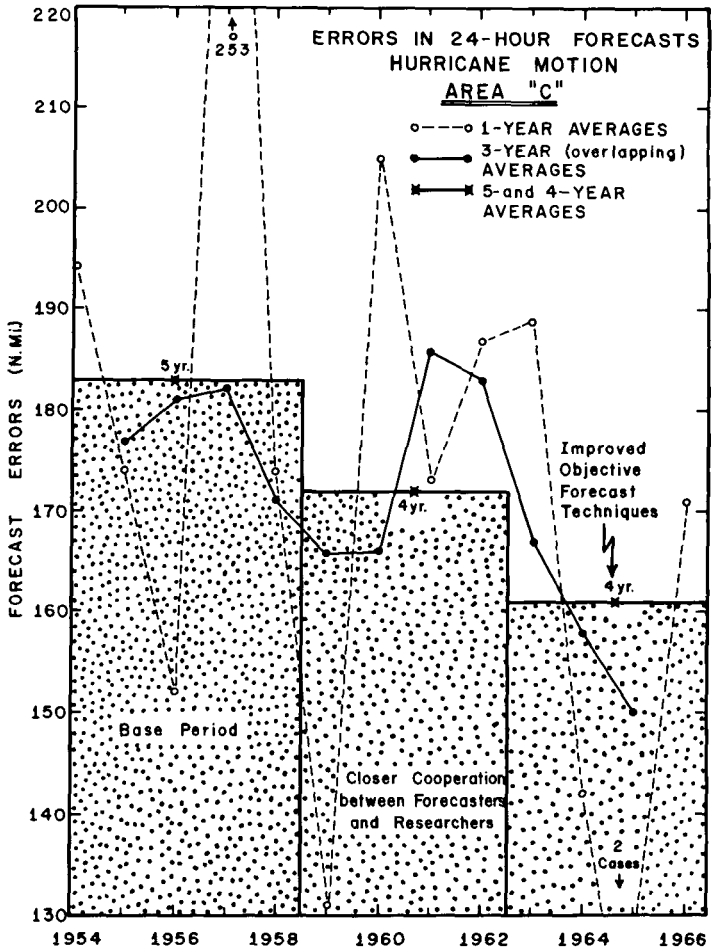

FIGURE 3.—Same as figure 2 except data are for area C.

length of the forecast period was changed slightly beginning in 1967 which makes comparison of results with those of earlier years awkward, and 3) a new and improved objective technique, NHC-67 [8], was used for the first time as an aid by the forecasters, and it is believed that 1 yr. is too short a time to evaluate its impact on the official forecasts.

One might argue that the storms were easier to forecast in the latter periods. A partial check of this possible explanation can be made by comparing the accuracy of the official forecasts with those based on climatology. The latter were made using as a forecast the most likely motion for the storm location as indicated in a study by Colón [1]. The errors of the official forecasts have consistently been less than those of such climatological forecasts and the superiority of the former has increased with time. For the period 1954–58 the mean errors of the official forecasts were only 60 and 77 percent of the mean errors for the climatological forecasts for areas B and C respectively. For the period 1963–66 these were further reduced to 55 and 64 percent respectively. Thus, this check supports the idea that the forecast accuracy improved rather than the idea that the storms were easier to forecast in the later years.

3. MANNER IN WHICH FORECASTS WERE MADE

During the period of this experiment the Weather Bureau has had five hurricane forecast offices: San Juan, New Orleans, Washington, Boston, and Miami. Miami, throughout this period, has been the principal forecast office and has issued approximately 60 percent of the hurricane advisories. During all of this period the U.S. Navy has also had a hurricane forecast office. It has been the custom in Miami to coordinate the forecasts issued by the hurricane forecast offices involved. This, in most cases, involved at least one other Weather Bureau forecast office besides Miami and the Navy. In some years representatives of the National Meteorological Center at Suitland, Md., occasionally participated in the coordination. The forecasts were all made in a subjective manner. In most cases, however, in the later years reference was made to results of the objective techniques before the subjective forecast was prepared for official release.

4. DEVELOPMENT OF OBJECTIVE TECHNIQUES

At the time the formal forecast improvement program was started in 1959, four objective techniques were already available for testing. These were the Riehl, Haggard, and Sanborn [10] grid technique, the Miller and Moore [9] grid and persistence technique, the Travelers regression technique (T-59) developed by screening

procedure [13], and the steering technique using a barotropic model [3, 4]. Forecasts were made under semi-operational conditions by each of these objective techniques during the early years of the experiment. Comparisons of verifications were made to determine which technique performed best. In addition, a cooperative program was initiated between the National Hurricane Research Laboratory and the Travelers Research Center to develop an improved statistical forecasting technique and scientists at the National Meteorological Center continued efforts to improve the dynamical model [12]. The former resulted in another regression technique based on the screening procedure which was called the T-60 [14]. In later years Miller and his group progressively developed the NHRP-62 and the NHC-64 technique [7]. They also developed a Modified Miller-Moore technique. The NHC-64 system makes forecasts for periods of 12 to 48 hr. in advance. It has been tested on independent data for the years 1962–1967 and (until NHC-67 was developed) had consistently outperformed all of the other objective techniques, with the exception of the modified Miller-Moore procedure which provided forecasts for only 24 hr. in advance. These two gave essentially the same average error for 24 hr. in advance.

Results of verifications of hurricane motion forecasts made by various objective techniques and presented in figure 4 strongly suggest that the techniques developed in later years furnish more accurate forecasts than those available at the beginning of the experiment. All the forecasts were not prepared at the same time and, unfortunately, it is difficult to obtain a comparison between all the techniques for a large sample of homogeneous cases. A comparision, however, has been made between 30 forecasts made in 1964 by NHC-64 and each of three of the earlier techniques (Persistence, NWP, and T-59). The results are presented in table 2. The data in this table as well as those in figure 4 illustrate the improvement made in objective-type hurricane forecasting since initiation of the experiment.

After the NHC-64 technique was tested under operational conditions and selected as the best objective technique available by the end of the 1964 hurricane season, arrangements were then made for the National Meteorological Center (NMC) to prepare the NHC-64 forecast using as input parameters from the objective analyses prepared at the NMC. During the winter of 1964–65 these test forecasts were verified and found to have approximately the same accuracy as those that had been made by the researchers working at Miami from data read from the hand-analyzed maps of the Miami Hurricane Center. Arrangements were then made for the NHC-64 statistical forecasts to be prepared on an operational basis during the 1965 season at the NMC. At about this time the procedures there were changed so that a preliminary analysis was made at observation time +1½ hr. Tests made during the 1965 season showed that NHC-64 forecasts of hurricane motion made from the preliminary and the final NMC analyses were of about equal accuracy. This is not surprising since many of the data near areas B and C are available by 1½ hr.

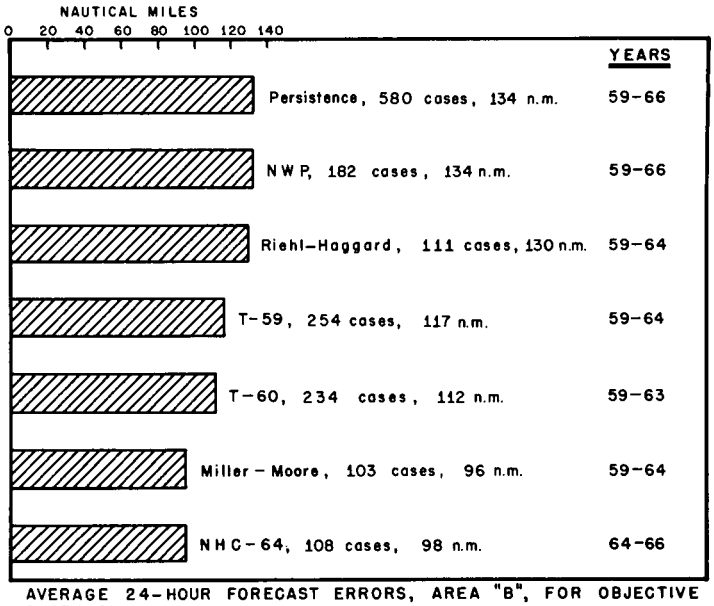

FIGURE 4.—Mean errors in forecasts of hurricane motion made by various objective techniques.

TABLE 2.—*Mean errors in 24-hr. forecasts of hurricane notion (n.mi.)*

Number of forecasts	Techniques			
	NHC-64	Persistence	NWP	T-59
30	120	143	142	139

after map time, and the usually good 12-hr. forecast of the flow patterns serves as first approximation for the analyses. By using hurricane forecasts made from the preliminary analyses it has been possible for the prediction by the NHC-64 system to be available in Miami before the official hurricane forecasts are prepared, and this was true for many of the hurricanes in 1965 and 1966.

5. EXPLANATIONS FOR THE IMPROVEMENT OF HURRICANE FORECASTS

Improvement in the forecasts can probably be attributed to a combination of the following four causes:

1) Improvement of objective techniques for forecasting hurricane motion,

2) Improvement in the general skill of the hurricane forecasters,

3) Cooperation between the researchers and forecasters which provides for focusing a greater amount of manpower on the problem of developing the hurricane forecasts, and

4) Improved and increased aircraft and radar tracking of hurricanes.

A comparison between average errors of the Weather Bureau forecasts and those of the NHC-64 for common cases in 1964–66 is given in figure 5. Direct comparison is difficult because the forecasts are made for slightly different time periods even though both types are called 24-hr.

forecasts. Forecasts were made by the NHC-64 system from data observed at 00 GMT and 12 GMT for the succeeding 24 hr. The Weather Bureau made corresponding forecasts for 24-hr. periods beginning respectively at 04 GMT and 16 GMT. In most cases few additional data were available to the forecasters beyond those used in making the analyses from which the corresponding NHC-64 forecast was prepared. If the beginning of the forecast period is defined as the time when the data are observed rather than when the forecast is released, the Weather Bureau forecasts are for 28 hr. rather than for 24 hr. The magnitude of the mean forecast errors through the years has varied almost linearly with time according to Tracy [11].

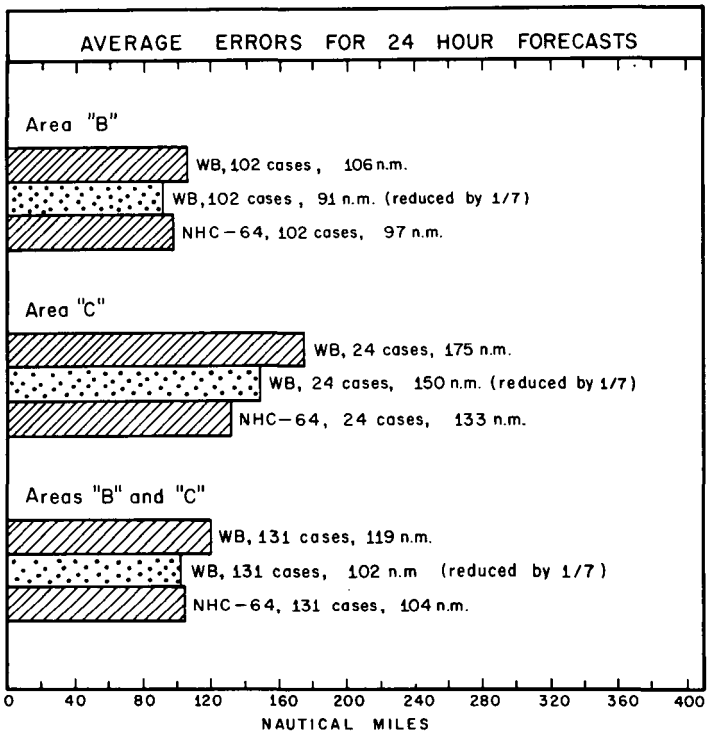

FIGURE 5.—Comparison of mean errors of 24-hr. hurricane motion forecasts prepared by the Weather Bureau and by the NHC-64 objective technique.

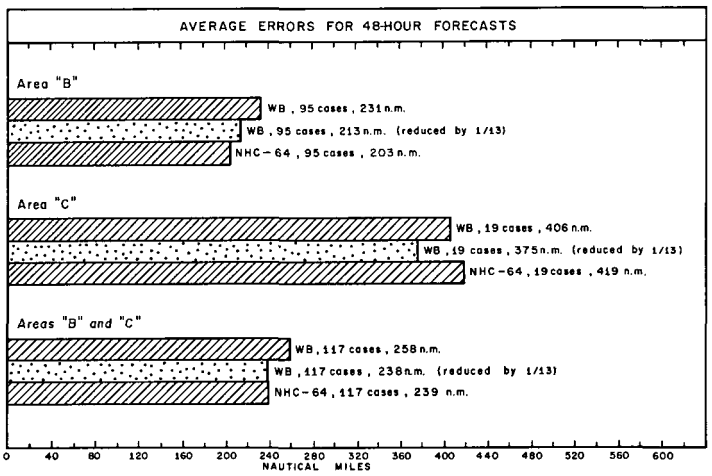

FIGURE 6.—Same as figure 7 except errors are for 48-hr. forecasts.

It may be fairer therefore to compare the errors of the NHC-64 technique with the errors for the Weather Bureau forecasts reduced by one-seventh. In any case the mean forecast errors for the Weather Bureau are presented in figure 5, both as actually computed and as reduced by this factor. Except for the slight differences in length of the forecast periods the samples are homogeneous.

There has been little difference in accuracy of forecasts issued by the Weather Bureau and those prepared by the NHC-64 technique if one accepts one-seventh as being the proper factor to use for adjustment of the mean errors due to differences in length of forecast periods. For the 24-hr. forecasts the Weather Bureau forecasts were slightly more accurate in area B and the NHC-64 were more accurate in area C. If all these cases where forecasts were made by both techniques are grouped together, the average error was 102 n.mi. for the Weather Bureau and 104 n.mi. for the NHC-64; that is, there was very little difference.

A similar comparison for the 48-hr. forecasts is presented in figure 6. In this case the Weather Bureau forecasts are for the period extending about 52 hr. after the data are observed so one-thirteenth is the factor used to make the time periods more nearly comparable. In this case the NHC-64 did slightly better in area B and the Weather Bureau did better in area C. Again there was little difference when all the cases were combined.

One cannot be certain whether the improvement in forecast accuracy between 1958 and 1966 should be largely attributed to improved skill of the hurricane forecasters or to the improved objective techniques. It is clear, however, that the official forecasts had to be better in 1964–66 than they were in the earlier years or the objective technique would have produced better results than the subjectively prepared official forecasts.

It is believed that the variation in data available cannot account for much of the improvement of the forecasts. The variation by years in amount of data at the upper levels is illustrated in figure 7. The number of such observations

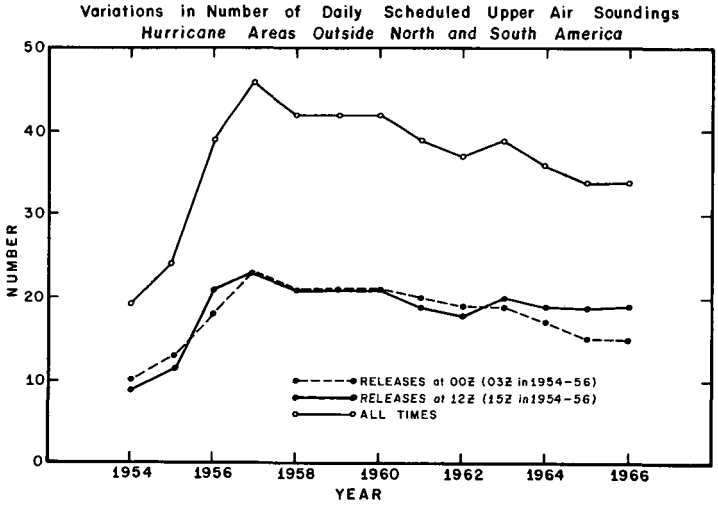

FIGURE 7.—Variation in number of scheduled upper air soundings per day in areas A and B (see fig. 1), but outside Continental North and South America.

per day in areas B and C but outside North and South America more than doubled between 1955 and 1957 largely through the cooperative efforts of the National Hurricane Research Laboratory and several of our neighboring countries. These efforts resulted in the establishment of eight new rawinsonde stations. In recent years the Atlantic Missile Range has reduced the number of upper air observations made at their rawinsonde stations and fewer upper air reports have been received from Cuba. Since 1960 the number of upper air observations has steadily decreased. Thus, if availability of these data were the only criteria, forecast accuracy should have improved between 1954 and 1958 and deteriorated since 1960. (It can readily be shown that the forecasts are more accurate in the areas of more frequent upper air reports. For example, compare average errors in areas A, B, and C as presented by Tracy [11].) More fixes on the hurricane center especially from aircraft and radar tracking were available in the later periods. These are believed to have balanced the effect of reduced amount of upper air data and in some cases may have contributed to forecast improvement. Satellite data, which have become increasingly available during recent years, have helped in the detection and tracking of the hurricanes—particularly in area A. They have not been used, however, in the development of forecasts of hurricane motion.

6. PLANS FOR THE FUTURE

The recent reorganization in the Weather Bureau calls for increased emphasis to be placed on the Miami Hurricane Forecast Center for the preparation of hurricane forecasts. The plans also call for this forecast center to have a group of hurricane specialists who will work on the forecast problem all the year. The National Hurricane Research Laboratory is continuing efforts to improve the statistical forecasting techniques. Current efforts involve more sophisticated typing of the data and incorporation as predictors of ouptut from the 500-mb. prognostic information available from the dynamical models run at the National Meteorological Center. The National Hurricane Research Laboratory is also supporting research efforts to develop improved dynamical models for forecasting hurricane motion. This is being done not only internally in the Laboratory but under a grant to the Massachusetts Institute of Technology. One of these models is being tested operationally in 1968. Preliminary tests indicate that it may support further improvement in the accuracy of the hurricane forecasts. The National Meteorological Center at Suitland, Md., also has plans for improving the dynamical model used for forecasting hurricane motion. Significant improvement in the forecasts may also result from efforts to improve hemispheric forecasts of the upper air flow being made at the National Meteorological Center.

7. CONCLUSION

The joint efforts of the forecasters of the Weather Bureau and the researchers in and those supported by the National Hurricane Research Laboratory (both components of ESSA) and improved data obtained by ESSA, the Air Force, and the Navy, have resulted in improved hurricane forecasts as revealed by tests conducted over the last 14 yr. During the 8 yr. from 1959 to 1966 there has been a reduction in the average error of forecasts of hurricane motion of 10 to 12 percent depending on the area.

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